# Laurentian Great Lakes Ice and Weather Conditions for the 1998 El Niño Winter*

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## ABSTRACT

Winter 1997/98 occurred during one of the strongest warm El Niño events, and the Great Lakes experienced one of the least extensive ice covers of this century. Seasonal maximum ice cover for the combined area of the Great Lakes was the lowest on record (15%) relative to winters since 1963, a distinction formerly held by winter 1982/83 (25%), which was also an exceptionally strong El Niño winter. Maximum ice covers set new lows in winter 1997/98 for Lakes Erie (5%), Ontario (6%), and Superior (11%), tied the all-time low for Lake Huron (29%), and came close to tying the all-time low on Lake Michigan (15%; all-time low is 13%). Here the authors compare seasonal progression of lake-averaged ice cover for winter 1982/83, winter 1997/98, and a 20-winter normal (1960–79) derived from the NOAA Great Lakes Ice Atlas and discuss the 1997/98 ice cover in detail. Winter air temperatures in the Great Lakes were at or near record high levels, storms were displaced farther to the south over eastern North America, and precipitation was below average in the northern portion of the Great Lakes region. The Northern Hemispheric synoptic flow patterns responsible for this winter weather, the Great Lakes winter severity over the past two centuries, and impacts of this mild winter are briefly discussed.

## 1. Introduction

Winter 1997/98 followed the start of one of the strongest El Niño Southern Oscillation (ENSO) events of this century (Bell and Halpert 1999). (Winter 1997/98 will sometimes be referred to as winter 1998 for the sake of brevity.) Much-above-average temperatures in the tropical Pacific Ocean that started in the spring and summer of 1997 were the precursors of mild weather and a reduction of strong storms in the Great Lakes the proceeding fall and winter. The lower frequency of strong storms, above-average water levels, and below-average ice formation in the Great Lakes combined to provide ideal conditions for ship-

ping in fall and early winter (Associated Press 1998). Ice cover was the lowest since systematic observations of ice cover started in 1960, and winter 1998 ice cover was among the lowest of the twentieth century. Below-average snowfall and above-average temperatures in the Great Lakes region (Hoogterr 1997; Pyen 1998) resulted in hundreds of thousands of dollars of savings for road salt and sand, but it also resulted in lost revenues for winter sports businesses associated with downhill and cross-country skiing, snowmobiling, and ice fishing. The much-above-average winter temperatures meant cost savings for natural gas and electric utility customers in the Great Lakes states (Tomlinson 1998).

Here we describe the ice cover and ancillary data of this benchmark winter and place it in a historical perspective. The synoptic atmospheric circulation pattern associated with the winter weather, winter air temperatures, and the seasonal progression of ice cover are discussed. The 1997/98 winter is ranked as one of the mildest over the past two centuries. Lake-averaged seasonal progression of ice cover is compared to a 20-winter (1960–79) normal and to winter 1983, which also occurred during one of the strongest El Niño events of this century. The annual maximal ice cover in winter 1997/98 is compared to the lowest ice covers over the past 35 winters for each of the Great Lakes.

The impact of the mild 1998 winter on U.S. Coast Guard assistance to shipping during winter, on Great Lakes water levels, and on some aspects of the winter lake ecology are also discussed.

## 2. Synoptic description of winter temperature and circulation during ENSO

### a. 1997/98

The upper-air general circulation during winter 1997/98 was influenced significantly by the impressive El Niño conditions that were observed at the time (Bell and Halpert 1998, 1999). The circulation was characterized by flow that was considerably less diffluent than normal over the central and eastern North Pacific with the near-absence of the mid-Pacific trough, which resulted in comparatively more zonal flow than normal and a stronger and eastward displaced Pacific jet stream (Fig. 1). These conditions essentially flooded much of the United States with flow of maritime origin and helped to reduce the frequency of polar air outbreaks into the country, resulting in warmer than normal winter conditions over much of the northern and central states. This anomalous flow pattern was a direct response to the anomalously warm water along the entire near-equatorial tropical Pacific (Bell and Kousky 1999) and was associated with numerous storms that flooded parts of California, the Southwest, and the Gulf Coast states.

During December 1997, the 1000–500-hPa thickness (Fig. 2), which is proportional to the mean temperature in the air column between these two levels, was 30–120 m above normal over the extreme northern United States and much of central and southern Canada, indicating milder than normal conditions in those regions. Over the Great Lakes, the 1000–500-hPa thickness was near normal in the south and more than 60 m above normal over most of Lake Superior. Surface temperatures during the month (Fig. 3) ranged from 1°C above normal in the southeastern portion of the region to > 5°C above normal over western Lake Superior.

In January 1998, positive 1000–500-hPa thickness anomalies (Fig. 2) extended south and east of the December 1997 locations as the 500-hPa ridge flattened in the western states and the mean 500-hPa trough in the eastern portion of the country filled, resulting in abnormally zonal flow aloft. Furthermore, the trajectory of the mean 500-hPa flow into the north-
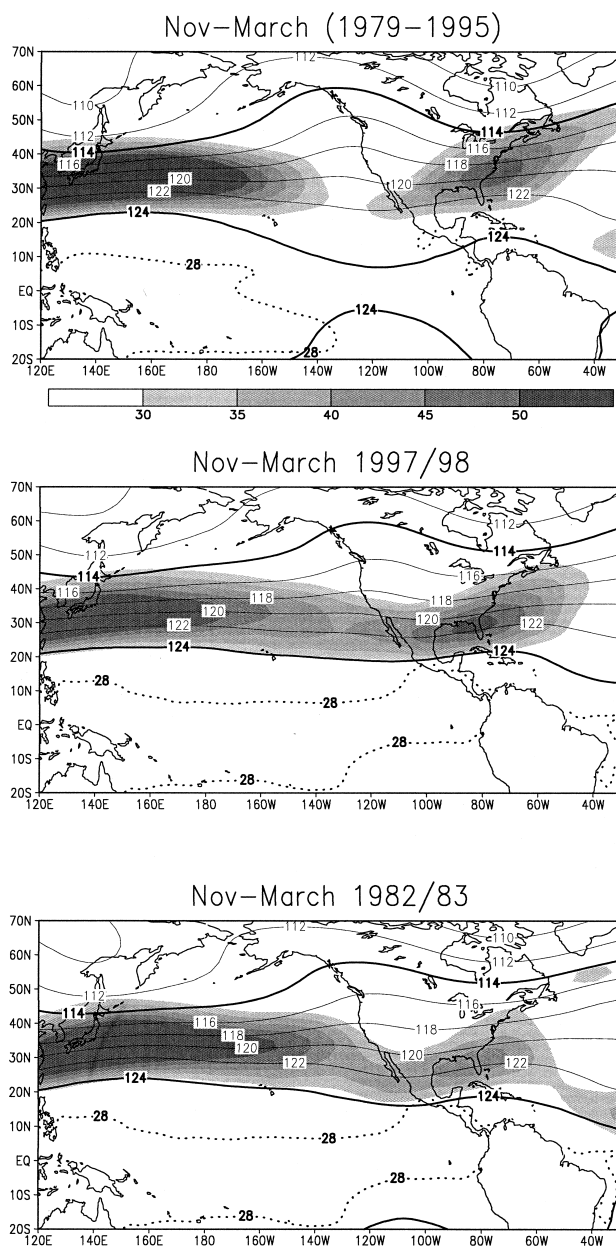


FIG. 1. Mean geopotential height (contours) and wind speed (shading) at 200 hPa for the period Nov–Mar for the 1979–95 base period (top), 1997/98 (middle), and 1982/83 (bottom). Height units are meters (× 100) and wind speeds are in m s⁻¹. Dotted line denotes area where sea surface temperature exceeds 28°C for the period. Atmospheric data are from the NCEP–NCAR Reanalysis Project (Kalnay et al. 1996).

ern and central states indicates an origin from the tropical and subtropical Pacific (Fig. 2) and therefore relatively warm temperatures. The maritime nature of the flow is reflected in the surface temperature anomalies (Fig. 3), which ranged from 3° to more than 6°C above normal over the entire Great Lakes region during the month.

**Dec 1997**

**Dec 1982**

**Jan 1998**

**Jan 1983**
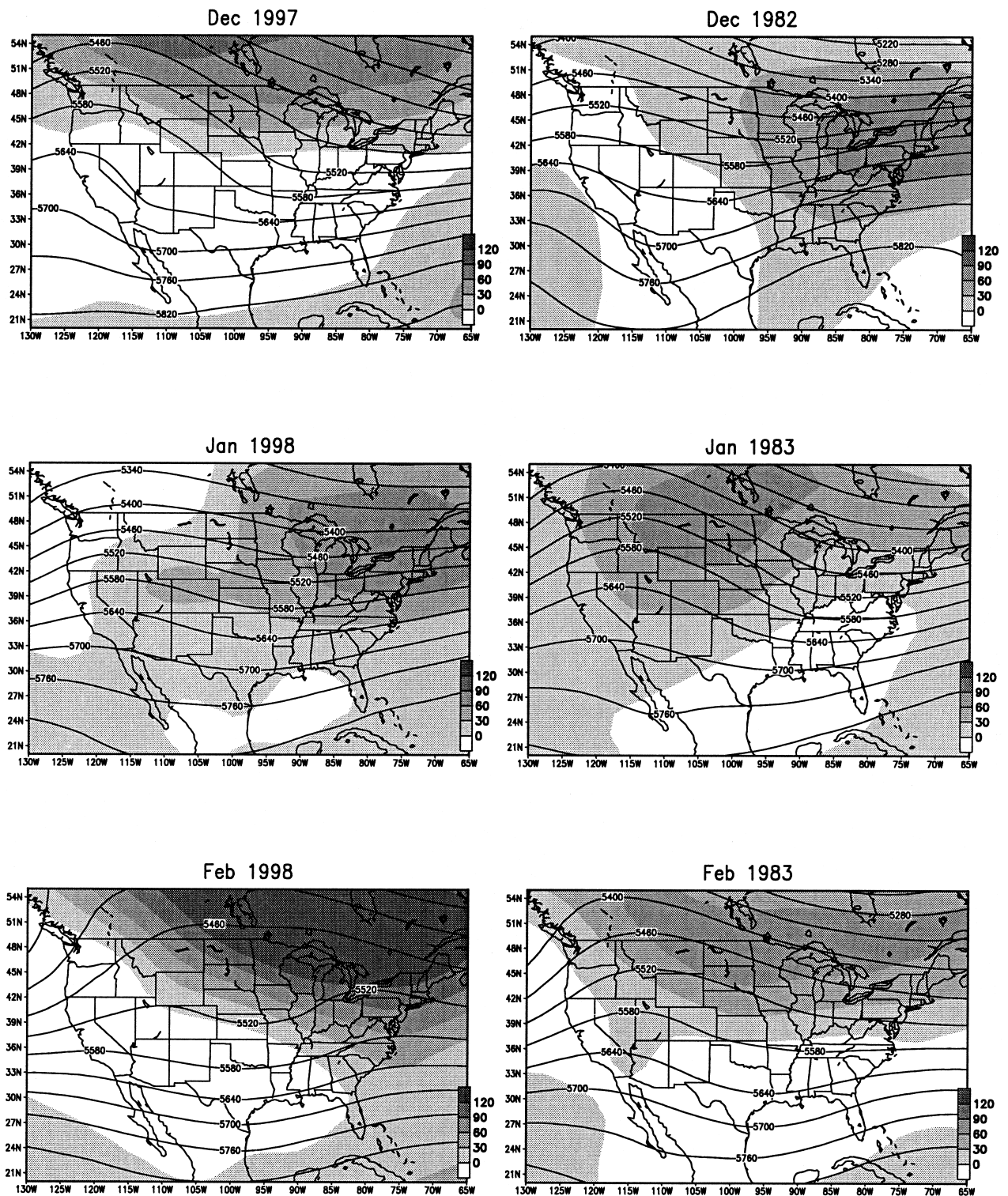
**Feb 1998**

**Feb 1983**

FIG. 2. 500-hPa geopotential height (contours) and 1000–500-hPa thickness departures from normal (shading) for Dec 1997, and Jan and Feb 1998 (left), and for the same months during 1982/83 (right). Units for both fields are meters. Data are from the NCEP–NCAR Reanalysis Project (Kalnay et al. 1996).

An enormous warming occurred during February 1998, as surface temperatures (Fig. 3) ranged from 5°C above normal over Lake Erie and Lake Ontario to

6°–8°C above normal over the remaining Great Lakes. Not surprisingly, significantly warmer than normal lower-tropospheric air temperatures (Fig. 2) were ob-
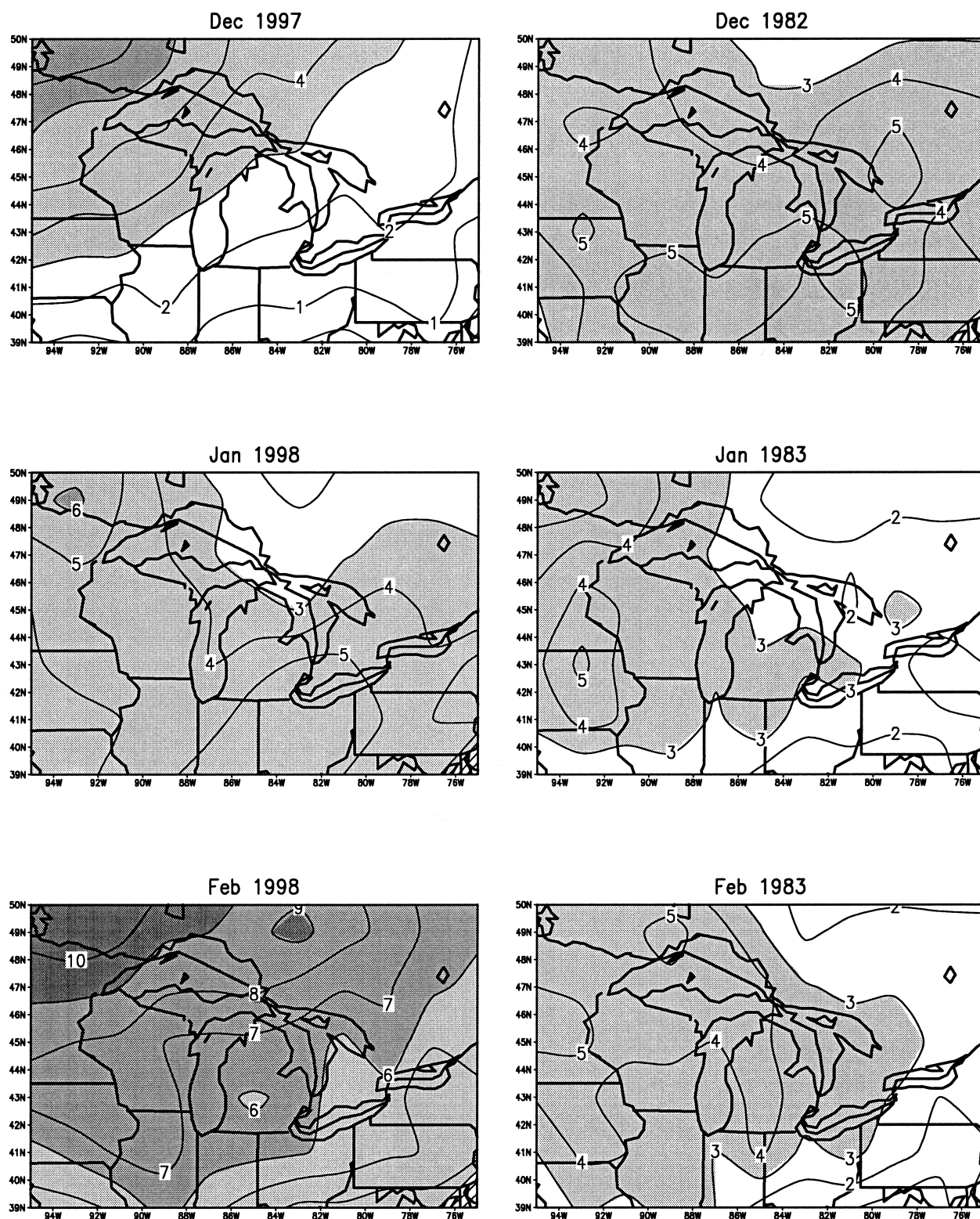
FIG. 3. Surface temperature departure (°C) from normal (1961–90 base period) for the Great Lakes region for Dec 1997, and Jan and Feb 1998 (left), and for the same months during 1982/83 (right). Light, medium, and dark shading indicates positive departures in excess of 3°, 6°, and 9°C, respectively.

served during the month as indicated by 1000–500-hPa thickness anomalies in excess of 120 m above normal over most of the lakes. Again, strong midlevel flow of maritime origin was observed during this month, and air of polar origin was far to the north.

### b. Comparison with other strong El Niño winter seasons

The last El Niño of comparable magnitude began in mid-1982 and extended into the summer of 1983. During the 1982/83 winter season, the 200-hPa geopotential height field and jet stream over the North Pacific were very comparable with the 1997/98 event (Fig. 1). During both events, the 200-hPa height field was considerably less diffluent than normal over the central and eastern North Pacific, and the mid-Pacific trough was nearly absent, resulting in comparatively more zonal flow than normal and a stronger and east-ward displaced Pacific jet stream. For reasons dis-cussed above, warmer than normal winter conditions were the rule over much of the northern and central states during the winter seasons of both the 1982/83 and 1997/98 El Niño events. Note the Pacific jet stream intensity is comparable for both seasons, albeit stronger during 1997/98, as is the eastward extension of the jet core.

The tropospheric temperature structure during the 1997/98 winter was very similar to that observed dur-ing the 1982/83 winter season (Fig. 2). Surface tem-peratures were considerably warmer during the 1997/98 winter, especially during February 1998 com-pared to February 1983 (Fig. 3), as were the intensity of the lower-tropospheric thickness anomalies (Fig. 2). A preliminary study (Assel 1998) indicates a possible statistical link between the strongest warm El Niño events over the past half-century and the intensity of winter warmth in the Great Lakes region; however, it must be cautioned that El Niño explains only a por-tion of the seasonal variability in the U.S. tempera-tures; other sources of internal or natural variability such as the North Atlantic Oscillation, for example (Wallace and Gutzler 1981), also play a major role.

Comparisons with U.S. winter temperatures for other recent El Niño events for which reliable upper-air data exist (1965/66, 1968/69, 1972/73, 1986/87, and 1991/92) indicate that the Great Lakes region (and most of North America) was considerably warmer during the 1982/83 and 1997/98 events than during the other events listed above (not shown). Also, the up-per-air circulation patterns over the North Pacific dur-ing the other five El Niño winters, while similar in pattern to the stronger events, exhibited considerably less amplitude than observed during the 1982/83 and 1997/98 events (not shown).

### c. Precipitation

Shabbar et al. (1997) provides evidence that aver-age winter precipitation in southern Canada (includ-ing the northern Great Lakes region) tends to be below average during El Niño winters. Noel and Changnon (1998) also found that average winter cyclone fre-quency over the northeast region of the Great Lakes (centered at 45°N, 80°W) is significantly less for win-ters following moderate to weak El Niño events. More recent studies provide evidence that 1) winter storm tracks for the 1997/98 winter were displaced farther southward compared to non–El Niño years (Smith and Ledridge 1999), and 2) that January and February cy-clone frequency over the Great Lakes are significantly lower for El Niño years than for all other years (Angle et al. 1999). Total winter precipitation in the Great Lakes region ranged from average to above average in the south portion to below average in the north dur-ing winter 1998 (NOAA 1998).

The influence of the El Niño on the winter precipi-tation is illustrated by Fig. 4. Extremely low precipi-tation occurred over the Lake Superior basin between November 1997 and February 1998 (Fig. 4a), where the winter of 1997/98 was the driest in the 50-yr pe-riod 1948–97. The El Niño years are fairly well dis-tributed throughout the distribution but are not included in the upper 10%. The same pattern did not hold true for the lower lakes represented by Lake Erie (Fig. 4b). For Lake Erie the winter brought well-above-average precipitation. Thus it would appear that the most critical conditions occurred on the Lake Supe-rior basin, which caused a large drop in winter levels but did not affect the lower lakes in the same manner.

## 3. 1998 winter severity in historical perspective

### a. Local winter severity

Annual maximum freezing degree day (FDD) ac-cumulations, that is, the accumulated departure of the mean daily air temperature from 0°C starting in au-tumn and ending the following spring, are used as an index of local winter severity at a specific site in the Great Lakes (Assel 1980, 1986). Positive accumula-tions of FDDs correlate well with ice cover formation (Assel 1991). The date of maximum FDD accumula-
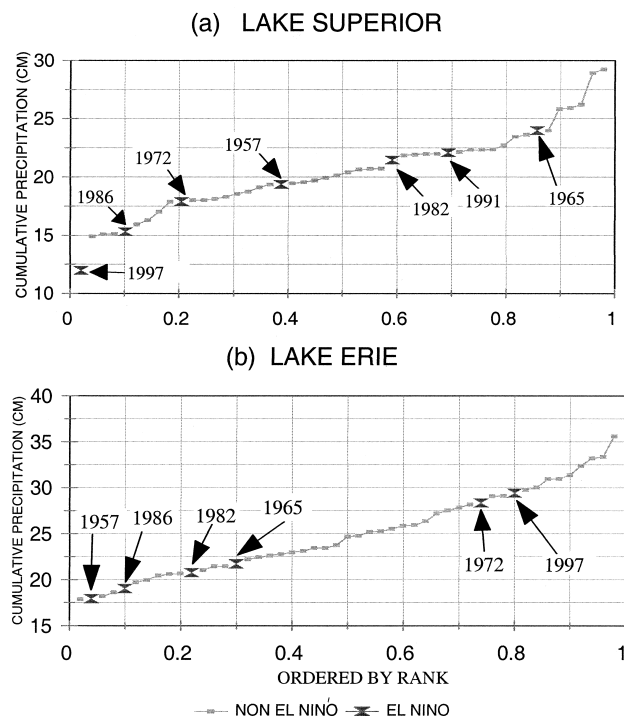
FIG. 4. (a) Lake Superior and (b) Lake Erie cumulative winter precipitation (Nov–Feb), for the years 1948/49 through 1997/98, sorted by yearly seasonal totals and showing the seven strongest El Nino events (available online at http://www.cdc.noaa.gov/~kew/MEI/).

tions in a given winter is important in that it separates a period generally favorable to ice formation from a period favorable for ice loss. Maximum FDD accumulations given in Assel et al. (1996) are updated for the winters of 1995, 1996, 1997, and 1998 in Table 1. The maximum FDD accumulations for winter 1998 are among the lowest (ranks 1, 2, and 3, where rank 1 is the lowest) of the twentieth century and are similar to the expected average seasonal maximum FDD accumulations for simulated $2\times CO_2$ scenarios (see Table IV of Assel 1991). This is quite remarkable and provides evidence that winter 1998 is a benchmark for both below-average winter severity and below-average ice cover on the Great Lakes. The date of maximum FDD accumulation on Lake Erie, at the southern portion of the Great Lakes, occurred in the fourth week of January and was about 3–6 weeks earlier than the long-term average; and maximum accumulations were less than 20% of the long-term average. The date of maximum FDD accumulations on Lake Superior, at the northern extreme of the Great Lakes, occurred the fourth week in March, about a week earlier than the long-term average; and maximum accumulations were less than 50% of their long-term average. Seasonal

maximum FDD characteristics on Lakes Huron and Michigan in general varied between these two extremes.

### b. Regional winter severity and modeled regional ice cover

A regional winter severity index (WSI) is defined as the November through February average of the monthly average temperatures at Duluth, Minnesota; Sault Ste. Marie, Michigan; Detroit, Michigan; and Buffalo, New York. The WSI for the 1983 ENSO winter ranked as the 10th lowest over the past 200 years (1783–1983) (Assel et al. 1985). The WSI for winter 1998 ranks as the sixth lowest over the period 1783–1998 (Table 2), and the third lowest, after 1932 and 1919, for the winters of the twentieth century. A regression model of the combined annual maximum ice cover extent for the five Great Lakes (standard error of 11.8% and $R^2$ of 0.606) given in Assel et al. (1996) is used here to place the 1998 ice cover in historical perspective over the past 200 years. Using that regression model, winter 1998 ice cover for the combined area of the Great Lakes was modeled to be about 18% (the observed value was 15%). The *modeled* ice cover for the warmest 10% of winters (Table 2) over the past 215 years ranges from 43% to 0%.

### c. Implications of strong El Niño on the WSI and Great Lakes ice cover

Assel (1998) compared the WSI and annual maximum ice cover for the six strongest warm ENSOs relative to other winters since 1950, excluding winter 1998. He found that the WSI averaged 1.2°C higher, and modeled annual maximum ice cover averaged 15% lower for the winters following the onset year of a strong warm ENSO event relative to the average of all other winters in the 1950–94 base period. Assel and Rodionov (1998) also found that annual maximum ice cover for a 28-winter record (1963–90) tended to be below average during the year after the start of a strong El Niño event. Our results are in agreement with these earlier studies (Table 3). We found that winter 1998, the second strongest El Niño since 1950, had the lowest WSI and lowest ice cover relative to the other six strongest ENSO events since 1950.

## 4. Great Lakes ice cover

### a. Data and analysis methods

Ice charts depicting the spatial distribution of ice concentration, produced by the Canadian Ice Service

TABLE 1. Winter 1998 maximum FDD characteristics compared to 1898–1998 average.

| | Accumulated freezing degree days | | | Date of maximum | |
|---|---|---|---|---|---|
| | Rank* | 1998 FDD** | Average FDD | 1998 | Average |
| **Lake Superior** | | | | | |
| Duluth, MN | 3 | 1345 (747) | 2808 (1256) | 24 Mar | 1 Apr |
| Sault Ste. Marie, MI | 1 | 883 (490) | 1796 (998) | 24 Mar | 2 Apr |
| **Lake Michigan** | | | | | |
| Green Bay, WI | 1 | 599 (333) | 1400 (778) | 21 Mar | 20 Mar |
| Milwaukee, WI | 2 | 231 (128) | 878 (488) | 10 Feb | 10 Mar |
| Chicago, IL | 1 | 153 (85) | 628 (349) | 26 Jan | 28 Feb |
| Muskegon, MI | 1 | 38 (77) | 662 (368) | 9 Feb | 11 Mar |
| **Lake Huron** | | | | | |
| Alpena, MI | 3 | 581 (323) | 1199 (666) | 25 Mar | 25 Mar |
| **Lakes St. Clair–Erie** | | | | | |
| Detroit, MI | 1 | 74 (41) | 574 (319) | 25 Jan | 6 Mar |
| Toledo, OH | 1 | 71 (39) | 563 (313) | 25 Jan | 27 Feb |
| Cleveland, OH | 1 | 50 (28) | 446 (248) | 21 Jan | 24 Feb |
| Buffalo, NY | 1 | 111 (62) | 637 (354) | 15 Feb | 11 Mar |

*Rank 1 is lowest FDD accumulation relative to the 101 winters between 1898 and 1998.
**Units are °F; FDD in °C are given in parentheses.

(CIS) and the National Ice Center (NIC), were used to analyze winter 1998 and winter 1983 ice covers, respectively. A detailed description of Great Lakes ice charts is available elsewhere (Assel et al. 1996) and is not included here for the sake of brevity. Lake-averaged ice cover for each Great Lake was calculated for 40 NIC ice charts for winter 1998, 20 CIS ice charts for winter 1983, and 9 normal ice charts (semimonthly ice charts from the last half of December through the last half of April) for a 20-winter (1960–79) base period (Assel et al. 1983). [Prior to winter 1998, winter 1983 had the lowest documented ice cover since systematic observations begin in the early 1960s (Assel et al. 1985).] Daily lake-averaged ice concentration was calculated (using linear interpolation) to facilitate comparisons among winters 1998, 1983, and the 20-yr climatology.

b. *Normal ice season*

The annual progression of ice on the Great Lakes consists of initial ice formation in December and January when the shallow areas of each lake form ice (Figs. 5a–e). During this initial ice formation period stable ice covers are formed in bays and harbors (Bolsenga 1988); extensive ice cover typically forms on Lake Erie the second half of January because it is so shallow [mean depth 19 m; mean depths of other lakes: Huron (58 m), Michigan (85 m), Ontario (86 m), Superior (148 m)]. Midlake ice typically occurs in February and March as the deeper lake areas cool sufficiently for ice formation (annual maximum ice extent is usually attained during this time; Table 4). Loss of ice cover can occur at any time during the winter due to the large heat storage capacity of the Great Lakes and action of winds to bring warmer waters to the surface or break up and

TABLE 2. Winter severity index for the 20 mildest winters[a] on the Great Lakes, 1783–1998.

| Rank | Winter | Severity index | Coldest month |
|---|---|---|---|
| 1 | 1931/32 | +0.1 | March |
| 2 | 1877/78 | −0.5[b] | Jan |
| 3 | 1881/82 | −1.0[b] | Jan |
| 4 | 1850/51 | −1.0[b] | Dec |
| 5 | 1918/19 | −1.3 | Feb |
| 6 | 1997/98[c] | −1.4 | Jan |
| 7 | 1889/90 | −1.5 | Mar |
| 8 | 1952/53 | −1.9 | Jan |
| 9 | 1948/49 | −2.0 | Feb |
| 10 | 1930/31 | −2.1 | Jan |
| 11 | 1982/83 | −2.2 | Jan |
| 12 | 1920/21 | −2.3 | Jan |
| 13 | 1794/95 | −2.5[b] | Jan |
| 14 | 1879/80 | −2.5[b] | Dec |
| 15 | 1994/95 | −2.5 | Feb |
| 16 | 1896/97 | −2.9 | Jan |
| 17 | 1990/91 | −3.0 | Dec |
| 18 | 1986/87 | −3.0 | Jan |
| 19 | 1862/63 | −3.0[b] | Feb |
| 20 | 1843/44 | −3.0[b] | Jan |

[a]Modified from Assel et al. (1985).
[b]Data prior to 1888 were not of sufficient quality to justify means with 0.1 precision. They have been rounded off to the nearest 0.5°C.
[c]Winter 1997/98 is the third mildest of the twentieth century, and 5 of the 11 warmest winters this century (shading) have occurred since winter 1983.

compact ice cover. However, the final dissipation of ice cover starts in March and is usually completed by

TABLE 3. The regional WSI and ice cover for the seven strongest MEI[a] events since 1950.[b]

| | WSI | Diff[c] | S-ICE[d] | O-ICE[e] | Diff[f] |
|---|---|---|---|---|---|
| 1957–58 | −3.5 | 1.2 | 44.1 | ND[g] | −14.9 |
| 1965–66 | −4.2 | 0.5 | 52.9 | 40.8 | −6.1 |
| 1972–73 | −4.5 | 0.2 | 56.7 | 49.9 | −2.3 |
| 1982–83 | −2.2 | 2.5 | 27.7 | 22.1 | −31.6 |
| 1986–87 | −3.0 | 1.7 | 37.8 | 27.3 | −21.2 |
| 1991–92 | −3.3 | 1.4 | 41.6 | 49.0 | −17.4 |
| 1997–98 | −1.4 | 3.3 | 17.6 | 15.3 | −41.4 |

[a]Multivariate ENSO Index (Wolter and Timlin 1993).
[b]Modified from Assel (1998).
[c]The difference (strong ENSOs minus base period average) positive differences indicate milder winters.
[d]Modeled ice cover.
[e]Observed ice cover.
[f]Difference [modeled minus 28-winter (1963–90) average (59%) of observed ice cover].
[g]ND, no data.

the end of April, with the exception of very limited shore ice.

### c. Winters 1998 and 1983 compared with normal ice season

During winters 1998 and 1983 the maximum ice cover for the Great Lakes did not exceed the normal for January (Figs. 5a–e and Table 4). Maximum ice coverage occurred in the last half of January and the first week of February in both these mild winters. The seasonal progression and extent of ice cover in winter 1998 was, with the exception of Lake Huron, less than in winter 1983. Ice was being lost the second half of February, a time when it normally reaches its maximum extent. The lack of ice on Lakes Erie and Superior in winter 1998 compared to even the mild 1983 winter is particularly stunning and may foreshadow expected ice conditions under a warmer climate (e.g., Assel 1991; Magnuson et al. 1997).

### d. Winter 1998 ice season

#### 1) DECEMBER

Initial ice formation started in the first week of December, primarily in the shallows of Lake Supe-
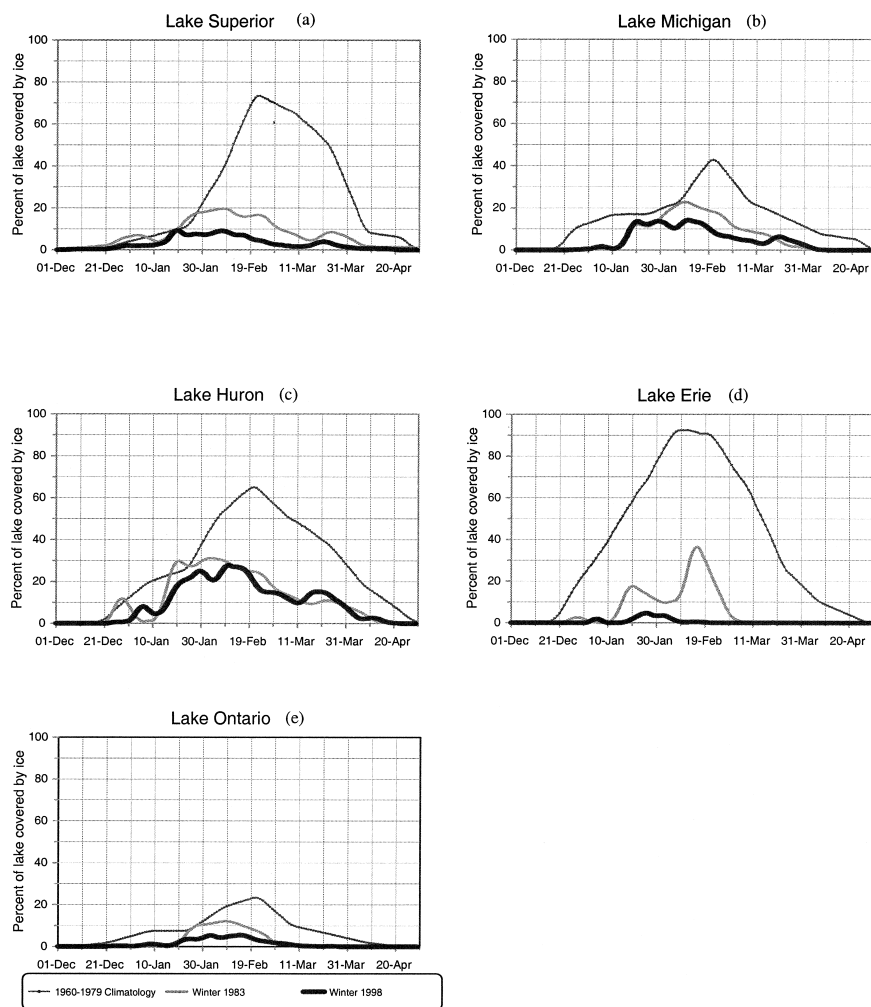
FIG. 5. The seasonal progression of 5-day running average ice concentration for winters 1997/98, 1982/83, and the normal for the base period 1960–79: (a) Lake Superior, (b) Lake Michigan, (c) Lake Huron, (d) Lake Erie, and (e) Lake Ontario. The thick curve represents winter 1998, the thin curve closest to the thick curve represents winter 1983, and the thin curve interrupted with circles is the 1960–1979 climatology.

rior. The upper-air circulation pattern during December included the normal ridge in the west and a trough in the eastern half of North America. The trough trending southwest to northeast across the northeast United States in the middle weeks of December brought colder polar air northwest of the gradient (over Lake Superior) and warmer maritime air to the southeast (over the other lakes). A stronger than normal southern jet stream kept the colder Canadian air masses from dropping vary far to the south. This atmospheric circulation pattern led to a disjointed pattern of initial ice formation on the Great Lakes. By 26 December, Lakes Superior, Michigan, and Huron had ice formation in the shallow embayments, while Lakes Erie and Ontario were still ice free. A cold arctic air outbreak starting in the last week of December brought new ice formation (by early January) to bays along the northern shores of Lakes Huron and Michigan, the perimeter of Lake Superior, and in the shallow western basin of Lake

TABLE 4. Lake averaged ice concentration (%).

| | Superior | | Michigan | | Huron | | Erie | | Ontario | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Date | % | Date | % | Date | % | Date | % | Date | % |
| Maximum 1998 | 16 Jan | 11 | 16 Jan | 15 | 6 Feb | 29 | 23 Jan | 05 | 30 Jan | 06 |
| 16–31 Jan, Normal* | | 12 | | 18 | | 30 | | 65 | | 07 |
| Maximum 1983 | 8 Feb | 20 | 8 Feb | 24 | 1 Feb | 32 | 14 Feb | 41 | 8 Feb | 12 |
| Maximum normal** | | 75 | | 45 | | 68 | | 90 | | 24 |

*Note that the maximum ice cover for winter 1998 occurred a month earlier than normal and was far less than the normal maximum ice cover and less than the maximum for the mild 1982/83 winter.
**Normal maximum ice cover (Assel et al. 1983) occurs 15–28 February.

Erie and over Lake St. Clair; Lake Ontario was still virtually ice free.

### 2) JANUARY

January temperatures were below freezing across most of the lakes as a second blast of arctic air made its way south on 11 January. This and other episodes of below freezing temperatures during the second half of January produced widespread growth of new (0–5 cm) and thin (5–15 cm) ice formation on all lakes. The maximum ice coverage for the winter season occurred on Lakes Superior, Michigan, Erie, and Ontario during the last half of January (Table 4) and Lake Huron was near its maximum at this time. The maximum ice cover occurred about a month earlier than normal. The 1998 maximum ice coverage on Lakes Superior, Erie, and Ontario established new lows (11%, 5%, and 6%, respectively). Lake Huron tied its all-time low (29%), and Michigan at 15% ice cover was within 2% of its all-time low (13%). It is also important to note that the ice thickness was much less than normal for season maximum ice extent. Winter

1998 had the lowest annual maximum ice cover for the combined area of the five Great Lakes (Fig. 6) over the past 35 winters: 1998 (15%); the next three lowest ice cover winters are 1983 (25%), 1987 (30%), and 1964 (32%) (data for 1996 and 1997 not available).

### 3) FEBRUARY

At the end of January the weather pattern shifted again to a more zonal flow, bringing above freezing temperatures to the southern portion of the Great Lakes. For the majority of the first three weeks of February temperatures were below freezing, but above normal. New ice formation was primarily less than 5 cm thick, and little growth of preexisting ice took place over that time period. The ice was much thinner than normal for February. An example of this is provided by comparing estimated ice thickness near the end of the first week in February in Whitefish Bay (southeastern end of Lake Superior) for winter 1998 with winter 1983 and with an average winter (1997). Estimated ice thickness near the end of the first week in February over most of Whitefish Bay was 15–30 cm
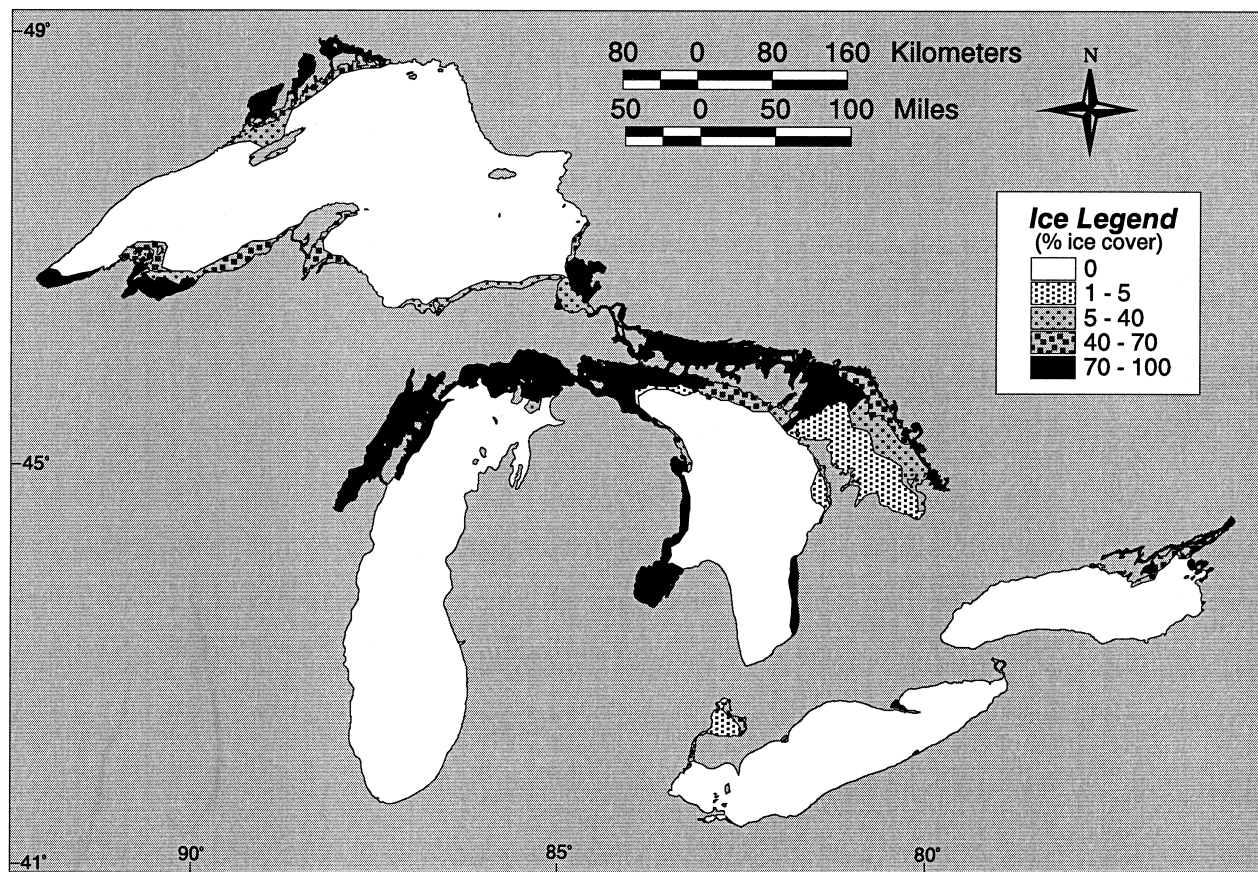


FIG. 6. Ice chart for 6 Feb 1998. This chart portrays the maximum. ice cover near the time that the combined area of the Great Lakes as a whole approached its maximum. value.

in 1983, 15–70 cm in 1997, and no more than 5 cm in 1998. The lack of thicker ice at this point of the winter increased the potential for early ice loss.

During the last week of February a low pressure system swept northward from Texas to central Wisconsin, bringing unseasonably warm temperatures to the Great Lakes. Cities along the lakes, especially in the east, experienced record high temperatures. Lake-averaged ice cover on 24 February 1998 was lower than the 20 winter composite minimum ice cover for the last half of February for Lakes Superior, Michigan, Erie, and Ontario (Table 5). This is remarkable in that winter 1998 represents a new lower limit of minimum ice cover for the second half of February relative to the existing climatology (Assel et al. 1983). Lake Erie, which is usually 90% ice covered during the second half of February was virtually ice free. During winter 1998 no ice was reported in the Buffalo area of Lake Erie; this has happened only one other winter since 1905, the winter of 1953 (International Niagara Working Committee 1998). The ice season for all practical purposes was completed on Lake Erie (and with the exception of the northeast bays on Lake Ontario as well) by the end of February.

4) MARCH AND APRIL

The bulk of the ice on the Great Lakes in March was located in Lake Superior (the three large bays along the northern shore and along the southern perimeter of the Lake), Lake Michigan (Green Bay and the Straits of Mackinac region), and Lake Huron (North Channel, Georgian Bay, and Saginaw Bay). Alternating periods of cold and warm temperatures brought short-lived increases and decreases in the ice covers in these areas, but no ice growth was analyzed in the midlake regions during March. After the passage of the end of February low and accompanying warm temperatures the storm track shifted over the United States. A low pressure center moved from British Columbia down through the Ohio Valley. This brought the third and final Arctic outbreak of the season over the Great Lakes and new ice growth during

the early and middle parts of March. Even with this new ice formation, Lake Superior and Ontario set new lower climatological limits for the first half of March (Table 5). Lakes Michigan and Huron were also near (slightly above) the composite minimum for the first half of March. High temperatures in the eastern half of the Great Lakes were 10°–14°C (50°–57°F) on 25 March. This led to the quick dissipation of the new ice formed in the beginning of the month, especially in Lake Ontario. Lake Ontario was ice free by 27 March. April started with cool temperatures for the first 2 weeks of the month and then a gradual warming trend was observed over the last 18 days. Lake Michigan became ice free during the second week of April, Lake Huron during the third week, and Lake Superior during the last week of the month. Lake Superior's ice cover during April was below the 20-yr composite minimum (Table 5).

## 5. Impact of the mild 1998 winter

A brief overview of the effects of the 1997/98 El Niño event on the Great Lakes with respect to winter ecology, water levels, lake shipping, and road maintenance is discussed. This is not intended to be a comprehensive or complete analysis but rather an indication of some of the potential effects of a mild winter on Great Lakes ecology and the regional economy.

TABLE 5. Half-month periods (X) for winter 1998 when ice cover was below a 1960–79 composite minimum.*

| | Lake | | | | |
|---|---|---|---|---|---|
| Half-month period | Superior | Michigan | Huron | Erie | Ontario |
| Dec 16–31 | . | . | X | . | . |
| Jan 01–15 | . | X | . | . | . |
| Jan 16–31 | . | . | . | . | . |
| Feb 01–14 | | . | . | . | . |
| Feb 15–28 | X | X | . | X | X |
| Mar 01–15 | X | . | . | . | X |
| Mar 16–31 | . | . | . | . | . |
| Apr 01–15 | X | . | . | . | . |
| Apr 16–31 | X | . | . | . | . |

*Assel et al. (1983).

### a. The winter ecology of the Great Lakes and winter "ice lands"

The ice cover formed in the shallow regions of the Great Lakes provides a stable platform (*ice lands*) in the shore zone of the Great Lakes in winter that affects the winter ecosystem of the Great Lakes including zooplankton production (Vanderploeg et al. 1992), whitefish recruitment (Brown et al. 1993), and migration patterns of herring gulls (Hebert 1998). These ice lands are also used for recreational activity (ice fishing) and for winter transportation (for both people and wildlife) between the mainland and islands such as Bois Blank Island in northern Lake Huron; Sugar, West Neebish, St. Joseph, and Drummond Islands in the St. Marys River (Hoogterr 1999); the Apostle Islands and Isle Royale in Lake Superior; and Bass Island in western Lake Erie. The formation of stable ice covers also influences the location and pattern of lake-effect snowfall in the shore regions of the Great Lakes. In winter 1998 the ice lands were not as stable or as long-lasting as in an average winter. The presence or lack of ice cover also affects the timing of a spring coastal plume in southern Lake Michigan, and the plume affects movement of lake sediments, availability of nutrients in the water column, and the lake biota (Eadie et al. 1996). During winter 1998, because of the lack of ice cover, a plume was observed in late January (Behm 1998), although the major plume formation took place during the second week of March. A recent study (Nicholls 1998) shows that phosphorus (*P*) concentrations (a key variable affecting lake eutrophication and the lake ecosystem) are negatively correlated with annual maximum ice cover extent on the Great Lakes (southern Lake Huron in particular) and that during winters after the start of strong El Niño events, *P* concentration is much higher than average. It is likely that this was the case in winter 1998.

### b. Great Lakes water levels

Due to drier than normal conditions through the winter, lake levels fell significantly. The effects were especially enhanced by the lack of snowcover in the upper Midwest. The spring snowmelt usually supplies a large proportion of the water that flows from Lake Superior southeast through the lakes system on into the Atlantic. With no snow to melt, the inflow water supply into the upper lakes was minimal. These effects moved into the lower lakes by the end of summer 1998. The average monthly level on Lake Erie reached the long-term average at the end of 1998 for the first time in many years.

Lake Superior water levels were the most affected by the 1997/98 winter conditions and El Niño. Seasonal water levels, derived by subtracting the 12-month November through October mean from each of the monthly means (Fig. 7a) show that there was insufficient snowmelt on the basin to sustain the normal seasonal rise in lake levels. The non–El Niño seasonal monthly averages show a more robust seasonal cycle than the average El Niño seasonal cycle as evidenced by the March minimums for 1997/98. The decline of Lake Superior lake levels after July 1998 has continued through March 1999 with that month having the lowest monthly March level since 1927.

The uniqueness of the seasonal cycle on Lake Superior is also illustrated by Fig. 7b, which shows the change in Lake Superior levels from a November base. The 1997/98 levels are well below the standard deviation for the November–October monthly levels. This is also reinforced by Fig. 7c, which shows the wide range in levels from various El Niño events. Again, the winter and spring of 1997/98 clearly stand out. An examination of the remaining Great Lakes did not indicate any unusual signatures that could be attributed to El Niño.

### c. Shipping

The mild winter produced cost savings across the Great Lakes. The most obvious was the major decrease in icebreaking support to commercial shipping on the lakes. Milder temperatures during the beginning of the season prevented ice formation even on the most northern waters of the Great Lakes system. The St. Lawrence Seaway was able to extend its navigation season to 29 December 1997. Ice conditions presented little difficulty to shipping through the winter, but due to earlier agreements the locks at Sault Ste. Marie closed on 15 January 1998. A smooth transition into the spring season resulted in the St. Lawrence Seaway and the Sault locks opening on 25 March 1998.

Coast Guard icebreaking operations were confined to rather routine track maintenance. Since the colder portion of the winter was during the first half, that type of activity was conducted in the Lower St. Marys River before the formal January closure. Operation "Taconite," which handles icebreaking on the Straits of Mackinaw, the St. Marys River, and Lake Superior commenced on 11 January and ended on 26 March with only 365 operating hours of work. Operation "Coal Shovel" on southern Lake Huron through Lake St. Clair and the connecting rivers into western Lake

Erie started on 17 January. The tugboat *Donald Hannah* was the only vessel needing assistance in the area all winter. She was moved through Saginaw Bay into the Saginaw River by the icebreaker Mackinaw on the first day. Total operating hours for the whole operation only amounted to 21. With little ice or icebreaking operations, even aerial reconnaissance was trimmed considerably. The Coast Guard's aircraft in the lakes area flew only 65 hours, and a specially remote sensor equipped aircraft from Corpus Christi flew 57 hours. Total hours for the winter season for the ninth Coast Guard district amounted to only 385.9—the least by far for over a decade (see Assel et al. 1996).

Individual shipping companies enjoyed the benefits of the minimal ice cover as well, according to the Lake Carriers' Association of Cleveland. No significant delays were reported during the spring opening by one company, compared with 91 lost hours in March 1997 and 746 lost hours in April. Another major shipping company did not log delays due to ice alone, but did track lost hours due to weather and ice combined. They lost 19 hours in March 1998 compared to 35 the previous year, and 273 in April 1998 compared to 348 in April 1997.

### d. Road maintenance

Many government agencies saved thousands of dollars in decreased winter road maintenance. State departments of transportation (DOT) around the lakes benefitted from the milder weather, but in some cases not as much as one would expect. Around the western lakes, although temperatures were several degrees above normal for the winter, precipitation averaged a little above normal and fell more frequently in the form of freezing rain rather than snow. This caused road crews to spread almost as much salt as they would have in a normal winter when more snowfall usually occurs. According to Tom Martinelli in the operations division of the Wisconsin DOT, total winter costs were $33.3 million
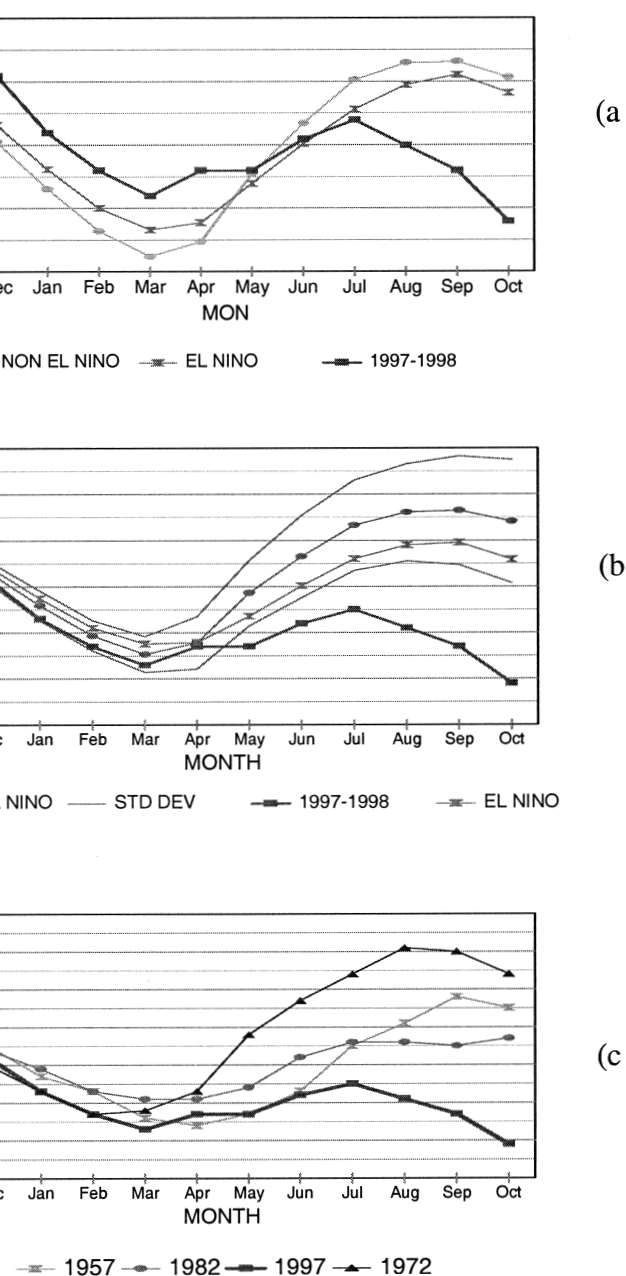
Fig. 7. Lake Superior (a) seasonal water level comparison, (b) monthly difference in lake levels from the Nov base level, and (c) monthly difference for selected El Niño events.

across the state compared to a 5-yr average of 35 million dollars. During the previous winter (1996/97) costs soared to 43.7 million dollars. This winter (1997/98), the state spread 410 000 tons of salt compared to 522 000 tons the previous season. During the drier winter, 1994/95, only 296 000 tons of salt were used. Farther east, the Ohio Department of Transportation saved about 3.5 million dollars in winter maintenance. The state normally expends $24 million and $20,547,000 was spent this year.

## 6. Concluding remarks

During 1997/98 the Great Lakes experienced one of the lightest ice seasons on record. All five of the Great Lakes were at or around the minimum ice cover record for the whole season. Three of the lakes—Erie, Ontario, and Michigan—set new records for minimum ice cover. Clearly the 1997/98 ice season was one for the record books. The development of the strong 1997/98 El Niño event had both economic and ecological ramifications for the lakes and the Great Lakes region. While El Niño is generally portrayed as a hazard with economic costs, benefits are also apparent as evidenced by the energy and transportation savings. The information on synoptic climatology, winter severity, and ice cover and the brief discussion of some of the effects of that event on the Great Lakes hopefully provides a useful reference for placing this winter in a historical context and perhaps a point of departure for further work.

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